

SAFELY SECURE FASTENERS IN CRITICAL APPLICATIONS

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ABSTRACT

It can be vital that bolted joints holding subassemblies together remain secure. Fasteners used to secure bolts and screws should resist the loosening caused by vibrations and dynamic loads, while keeping the ease of removability during maintenance. When a threaded fastener is subjected to vibration, the rapid movement causes a lowering of friction against the threads and a subsequent loss of preload. The loss of preload allows the fastener to vibrate loose and could lead to catastrophic consequences for critical applications. To mitigate the problem of unintentional bolt loosening, one must understand what parameters are critical in the bolted joint that affects this. The critical displacement threshold and the Junker vibration principle will be discussed to understand these self-loosening effect and the ways to reduce the risk.

There are many locking methods that are out on the market today to prevent this bolt self-loosening from occurring. While some are effective when the dynamic loads are mild, certain applications such as the aviation industry needs to have a locking method that can withstand harsh dynamic and vibratory conditions where self-loosening is not an option. The Junker vibration test will analyze these locking systems to compare among them how effective they are under extreme transverse loading conditions where bolt loosening is most susceptible. Several locking methods will be compared under this test procedure and analyzed.

INTRODUCTION

In every industrial applications imaginable, one could not help but notice the numerous bolted joint connections that goes into an equipment, component, or sub-assembly. Bolted joints are one of the most commonly used methods to bring parts together and to secure them in place. While they can generate enormous clamping force, as an added benefit, they can be easily disassembled without destructive means such with welding or other permanent joining methods.

However, there is an inherent weakness to this joining method by design. Without proper locking system in place, there is a potential under certain circumstances where the bolted joints can experience self-loosening. This is a phenomenon commonly observed under extreme vibrations and constant dynamic loadings where the joining parts begin to slide or shift. With many critical applications in the aviation industry that can experience both modes of external forces on a daily basis, it is imperative that the necessary preventative maintenance protocols are taken place. One of those protocols is to incorporate an effective locking system to the application's bolted joint. This paper will discuss the various locking methods and their effectiveness to prevent bolt self-loosening that are prevalent in this industry's environment.

As the primary topic of this paper is dedicated to understanding different locking systems' effectiveness from self-loosening, one should not discredit the importance of the other preventative maintenance protocols that also goes on in properly securing a bolted joint connection. These include proper installation and removal guidelines, appropriate tightening tool equipment, proper lubrication, routine maintenance, visual inspection and indexing, certified trained personnel, etc. A prime example of showcasing the importance of these practices from a complete bolted joint preventative maintenance perspective is the fatal accident case on August 20, 2007 with China Airlines Flight 120, Boeing 737-800, flight from Taiwan Taoyuan Internatinoal Airport to Naha Airport, Okinawa¹. Figure 1 shows the aftermath of improperly assembled downstop assembly nut on the leading edge slats which caused a fuel leak from the wing.



Figure 1. Wreckage of China Airlines Flight 120 following fire.

BOLT LOOSENING PRINCIPLE

When fastening a bolted joint, a moment is usually required for a threaded joint. The tightening moment (M_A) can be represented into three components (I.e., in Blume, Illgner 1988):

$$M_A = M_{T,P} + M_{T,F} + M_{H,F}$$

The moment generated by the thread pitch ($M_{T,P}$) leads to clamping force or preload. Preload is the force that compresses the clamped parts together by stretching the bolt in a torsional manner. The other two components are moments result from friction: $M_{T,F}$ is the friction in the thread and $M_{H,F}$ is the friction under the head of the bolt. To unfasten the bolt the moment M_L is required:

$$M_L = -M_{T,P} + M_{T,F} + M_{H,F}$$

The moment $M_{T,P}$ helps facilitate the unfastening of the bolt from its originally pretensioned state. This is evident that when the thread pitch moment $M_{T,P}$ is greater than the combined moments retained by friction $M_{T,F}$ and $M_{H,F}$, self loosening can take place:

$$M_{T,P} > M_{T,F} + M_{H,F}$$

Under normal friction conditions where static to mild dynamic loadings take place, the thread pitch moment is typically smaller than the combined moments due to friction. This occurrence where the bolted joint is stable and unfastening does not take place is called self-locking. This is the ideal state when designing parameters for bolted joints as this is its main purpose to keep the clamped parts together.

However, the self-locking condition can be neutralized by a small displacement in the bolted joint connection. When the bolted connections are subject to dynamic loadings, the joint could observe some micro-movements within its system. These movements particularly in the transverse motion is often the most susceptible for the bolted connections to experience self-loosening effect. These relative movements occur due to this external forces overcoming the frictional forces held by both the thread pitch and under the bolt head bearing surface. Once this relative movements starts and the frictional forces holding the bolted connections decreases, the self-loosening process begins.

To better understand how much movement it takes to begin this self-loosening phenomenon, we use the critical displacement threshold formula. The critical displacement threshold (d) can be calculated by:

$$d = \frac{\mu * F_0 * (L_p)^3}{12 * E_b * I}$$

Where: F_0 : Preload of the bolt

μ : Friction coefficient under the head of the bolt

L_p : Clamp length of the bolt

$E_b * I$: Stiffness of the bolt

A visual representation of the formula is shown below in Figure 2.

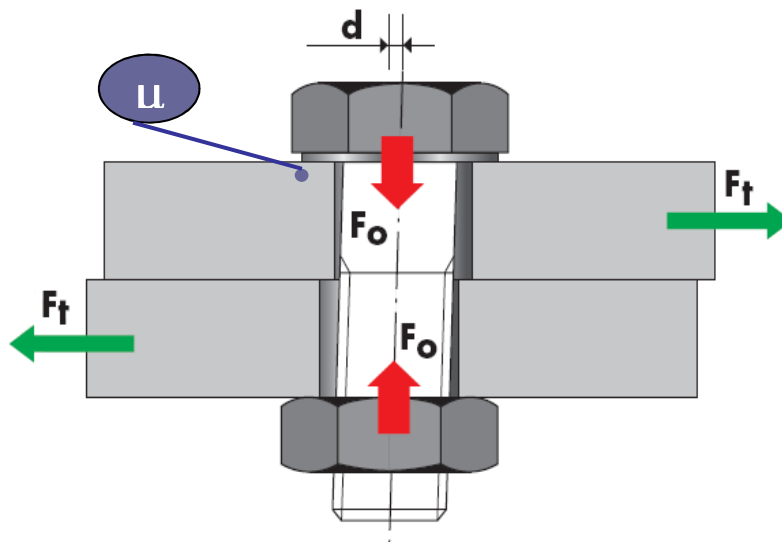


Figure 2. Model for the critical displacement threshold formula. F_t represents the external forces acting transversely from the joint under load.

For example, a M10 bolt with a preload of 30,000N, clamp length of 10mm, and friction coefficient under the head of the bolt of 0.15 will have an approximate critical displacement threshold of $4\mu\text{m}$. Therefore, if there is as much as $4\mu\text{m}$ of transverse movement there will be a risk for bolt self-loosening to occur. With this in mind, many design engineers will try to mitigate this issue by changing the bolted joint design to maximize this critical displacement threshold within the design parameters. Looking at how one can influence this threshold by increasing the clamp length is shown below in Figure 3. The figure below assumes the same

bolted joint condition described earlier. As one can see, there is an exponential relationship from increasing the clamp length of the joint to resist bolt self-loosening conditions.

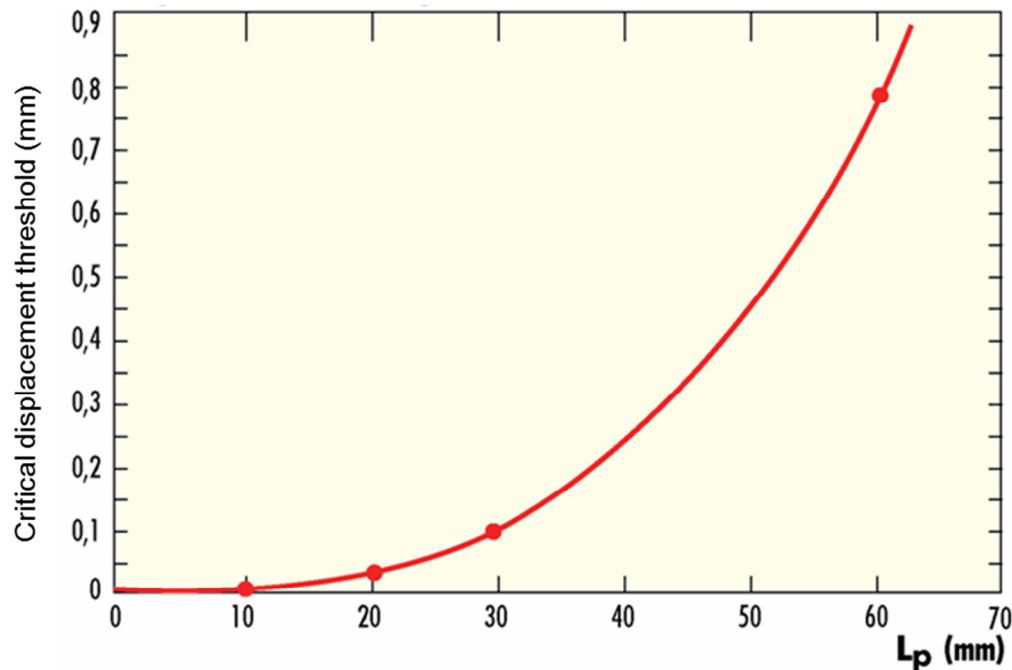


Figure 3. Shows the increasing benefit of increasing the clamp length on bolted joint to resist bolt self-loosening. Increasing the clamp length has an exponential relationship to enhancing the critical displacement threshold.

As discussed, increasing the clamp length is just one way to withstand the risk of bolt loosening. From the critical displacement threshold equation, there are several ways to accomplish this goal. Some of those methods are to:

- Increase the preload of the bolt
- Install smaller and longer bolts, i.e. more elasticity in the bolt
- Use fitted bolts to reduce possible transverse movements
- Enhance the friction coefficient

JUNKER VIBRATION TEST

This bolt self-loosening theory has been validated by a German engineer Gerhard Junker who has studied and conducted experiments on bolt self-loosening phenomenon in the late 1960's. The test bench he used to test various locking methods to rate the effectiveness from bolt self-loosening under transverse movements was named after him. The data collected from the Junker's vibration test allowed design engineers to specify fasteners and locking methods that would resist self-loosening under a wide range of bolting conditions. His testing methodology and test bench has been adopted into the international fasteners standards such as the DIN 65151 in 1969².

The Junker vibration test moves the bolted joint in a sheared direction along the plane by an eccentric rotating engine. While this movement is being conducted, the number of load cycles and clamp force are being measured simultaneously. These are monitored to observe how the

clamp force are affected throughout the duration of the transverse load cycles imposed. Some controlled variables on the Junker vibration test include amplitude of the transverse movement, hertz (cycles per second), clamp length, bolt/nut grade, and duration of the test.

The main objective for the Junker vibration test is to be able to compare and analyze how effective certain locking methods are under similar transverse loading conditions. Since it is often times very difficult to understand or monitor most applications at what frequency the joint is subjected to vibration, the Junker vibration test should never be compared with real life testing environments. The bolted joints that goes through the Junker vibration test is usually so severe that if it can withstand self-loosening the bolted joint would most likely stay in self-locking conditions in real life applications. The amplitude in the transverse movements for the Junker's vibration test is usually many times greater than the critical displacement threshold for a given joint.

JUNKER TEST ANALYSIS AND RESULTS

A Junker vibration test has been conducted among spring lock washer, double nut, nylon-insert nut, and Nord-Lock wedge-locking washer. The joint parameters are using M8 grade 8.8 bolt without lubrication with a grade 8 nut. The joint is tightened to 18kN of bolt preload for each test, which is approximately 75% of the bolt's tensile yield strength. The mating surface is mild grade steel and clamp length of 25mm. The Junker test bench is set to 40 cycles per second (40 hertz frequency) and the amplitude for the transverse movement at 0.3mm. The test duration will be set for 10 seconds with a running total of 400 load cycles. Figure 4 below shows a sample image of the Junker test with the testing parameters.

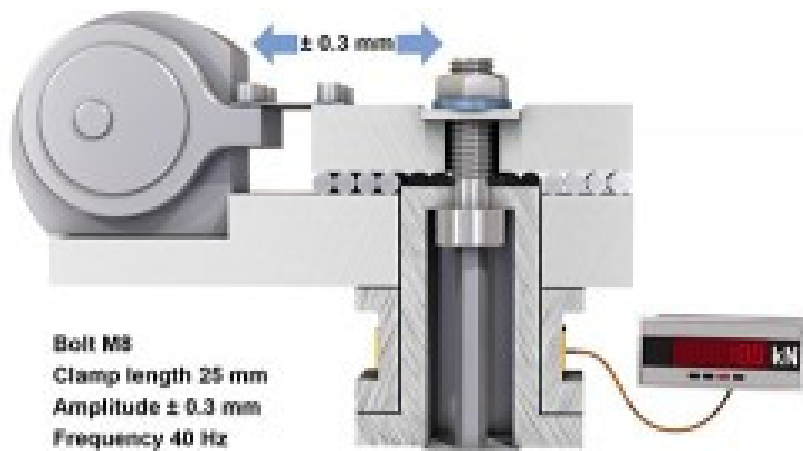


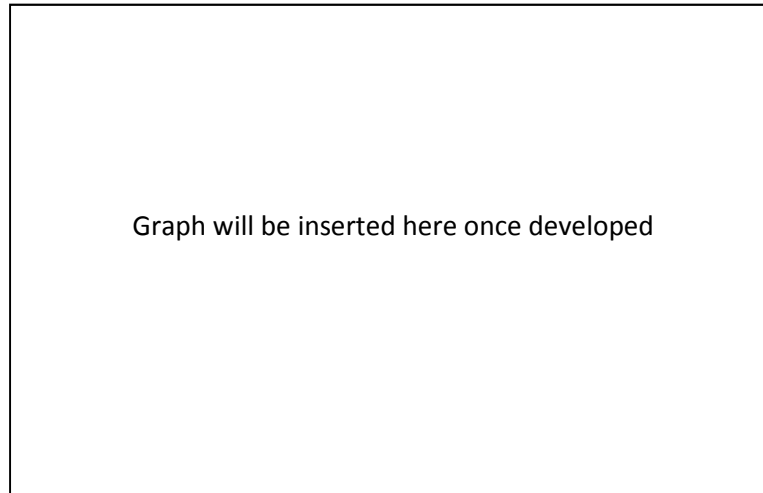
Figure 4. Image for Junker test set-up and test parameters.

Under Graph 1 we see the results from the Junker vibration test for the 4 different types of locking methods mentioned above. The spring lock washers immediately drops off after less than 100 load cycles into the test, making it among the locking methods tested the least resistant from self-loosening under extreme vibration and transverse movements in the joint.

The double nut failed completely at the end of the test duration of 400 load cycles. While the nylon-insert nut did not fail completely at the end of the test, there was only 2kN of preload retained in the bolted joint. The three locking methods all rely on high friction conditions to

resist the bolt self-loosening effect from occurring. However, these locking methods were not able to produce enough friction under the head of the bolt to counter the bolt loosening.

The Nord-Lock wedge-locking washers was able to retain bolt preload at the end of the 400 load cycles and maintain roughly 80% of the original preload when it started. The specially designed wedge-locking feature resists the bolt from turning as sliding occurs between the cams of the washers which are pitched at a greater angle than the threads.



Graph 1. Junker vibration test graph of the results for spring lock washer, double nut, nylon-insert nut, and Nord-Lock wedge-locking washer.

CONCLUSION

The Junker test results concludes that many of the common bolt locking methods used are friction-based principles where to a limited degree could withstand the dynamic transverse loadings. The Nord-Lock wedge-locking washer performed the best in terms of resisting bolt self-loosening significantly compared to the other locking methods. The slight decrease in clamp load is due to the inherent relaxation in the bolt under load and the settlement created by the serrations embedding into the mating surface and under the bolt head. This unique wedge-locking washers rely not on friction, but on wedge-locking principle and added tension when subject to nut-loosening.

While there are many other locking methods commercially available today on the market it is always important to review the bolted joint to first look into the joint design to see how one can increase the critical displacement threshold to resist self-loosening. However, from a designing aspect, not all joints can be manipulated to compensate for this criteria as it affects equipment efficiency, performance, and cost. Therefore, when certain joints are susceptible for bolt self-loosening is where various locking methods should be investigated. A mean to compare the self-locking efficacy of various locking methods is the Junker vibration test. Test parameters and joint configuration should be carefully studied and understood before conducting such test before taking the results into practical use.

Once a locking method has been carefully selected, a program for proper maintenance checks and procedures needs to be in place. Adding a locking method to a critical bolted joint is often necessary, but without the total preventative maintenance checks implemented catastrophic accidents and damages cannot be fully prevented.

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